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Reopening Mt. St. Helens: Mass Balance and Force Constraints on the May 18, 1980 Eruption

On May 18, 1980 a M5.1 earthquake triggered a landslide that exposed the cryptodome beneath the north flank of Mt. St. Helens. The explosions over the next few minutes blasted 2.5×10^{11} kg of material over approximately 500 km^2 exemplifying a previously little-known eruption style known as a "lateral blast" [*Kieffer,* 1981]. Studies of the eruption dynamics have often assumed that the initial impulse of this blast was horizontal. The material was pushed laterally out of the mountain and covered the devastated area. This assumption has lead to specific predictions of jet structure and a fairly detailed model of the blast dynamics [*Kieffer,* 1981]. I will argue that the initial momentum in the blast was not dominantly horizontal. Seismic evidence [*Kanamori & Given,* 1982] is compared by means of a simple flux model to the total mass in geologic record [*Moore & Sisson,* 1981] and it is seen that most of the initial impulse of the blast was vertical. The blast material subsequently fell down the mountain under the force of gravity to become the observed devastating supersonic flow.

Observations

Kanamori et al. [1982, 1984] observe a long-period horizontal seismic signal and a series of short-period vertical signals (Fig. 1). "Vertical" in *Kanamori et al.* [1984] means directed "significantly larger than 60°" which is subsequently interpreted as 80° - 90° from the horizontal. A more precise direction cannot be resolved from the seismic data. I will maintain this definition of "vertical" unless otherwise specified. The vertical observed pulses consist of two distinct sequences. The largest pulse of the first sequence peaked at 8:32:45.4. This time corresponds to a sudden increase in plume height in the Rosenquist photos of the eruption. A horizontally thrusted lateral blast such as that proposed by *Kieffer* [1981] should have a short-period (< 17s) horizontal signal corresponding to the thrust of about 1.7-5.4 x 10^{12}N starting around the same time. The absence of such a signal on the the seismic record is not conclusive by itself since *Kanamori et al.* [1984] mention that there may be a short-period (35 s) horizontal force as large as 10^{12}N masked by the much larger amplitude long-period signal.

The mass erupted at various stages of the eruption can be estimated by calculating the total mass of the corresponding geological deposits. This method neglects the mass of the gas ejected. Although the gas was volumetrically and dynamically important, it is unlikely that its mass exceeded a few weight percent [*Eichelberger & Hayes,* 1982]. Between 5.2-7.0 x 10^{11} kg of juvenile magmatic material was ejected from Mt. St. Helens on May 18, 1980 (*Christiansen & Peterson* [1981]; *Friedman et al.* [1981]). Approximately 20% of the total juvenile material is found in the blast deposit. This 1.2 x 10^{11} kg accounts for roughly half of the total mass of the lateral blast [*Moore & Sisson,* 1981]. The rest is termed "non-magmatic material" and includes country rock entrained in the blast. A mere 4.8×10^{10} kg of the blast deposit show the textural characteristics of airfall. It is worth noting for comparative purposes that the mass of the landslide, 5.8×10^{12} kg [*Glicken,* 1996], dwarfs any of the eruptive products.

Discussion

The simplest explanation for the observed vertical forces is that they are in response to the thrust of the mass ejected,

$$\dot{M}v = F \tag{1}$$

where $\dot{M}$ is the mass flux, v is the velocity of the jet and F is the force. All of the parameters are measured at the vent where the coupling of the jet to the Earth takes place. The velocity at the vent v is the sonic velocity for a choked flow. Eq. 1 allows the estimation of the total mass discharged vertically based on the forces recorded seismically. One might expect this mass to be equal to the blast airfall or a small fraction of the total blast deposit if the blast was primarily a horizontal jet.

For the sonic velocity at the vent as estimated in *Kieffer* [1981], 100 m/s, the total mass discharge calculated with Eq. 1 and the data of *Kanamori et al.* [1984] is 1.7 x 10^{12} kg. This value is almost 7 times the total material in the blast deposit and twice the total juvenile material ejected on May 18. Even with a velocity of 300 m/s, nearly the sound velocity in air, the total ejected mass would be 5.7 x 10^{11} kg which is over twice the total blast deposit and close to the eruption's total juvenile mass (Fig. 1.) The vent velocity v must be 600 m/s for the observed deposits to account for the total vertical ejected mass. Furthermore, the velocity is unlikely to be constant throughout each explosion. Near the beginning or end of each pulse the flow may be subsonic. The velocity v would be lower and hence the mass flux $\dot{M}$ required for the observed force would be even larger. In summary, for any reasonable vent velocity the mass ejected vertically greatly exceeds our initial expectations. According to the simple model of Eq. 1 more material was ejected vertically than can be accounted for in the total blast deposit. Of course, there may be substantial errors in both the geological deposit measurements and the seismic model, but even if both data sets are in error by a factor of 2, most of the mass was blasted vertically from the vent. If each of the vertical pulses represents a thrust, the mass balance considerations make it unreasonable to assume that the majority of the blast deposit was initially ejected horizontally. Before this assertion can be confirmed two alternate hypotheses must be considered: a) there was significant recycling of material in the explosions and therefore some of the mass was double-counted in the above calculations and b) every pulse does not represent a separate thrust event describable by Eq. 1.

The coincidence of the first set of thrusts over the first two minutes with the photographically documented expansion indicates that these thrusts arose from the depressurization of sections of the cryptodome. Since each section could only be depressurized once, no significant recycling of blast material occurred in the process. However, the second set of pulses from 15:34.6-15:35.3 may be explained differently. At approximately the time of these forces a plume was observed in rising from the Spirit Lake or Toutle River area 8-10 km north of the vent [*Moore & Rice,* 1984]. The most sustained and intense infrared was also observed during 15:34.4-15:34.7 [*Moore & Rice,* 1984]. *Moore & Rice* [1984] interprets these events as either the unroofing of previously undisturbed cryptodome material in the the landslide blocks or interaction with external water. The later interpretation would allow recycling of previously erupted material and would make the second half of the curve in Fig. 1 irrelevant. This would make the overall mass balance nearly match the total erupted deposit and hence is the interpretation favored by this analysis. However, the error in estimating the deposit mass from the geological evidence is too great to definitively require this recycling.

What if not all the pulses represent thrusts? It is possible that irregularities of the landslide movement could have produced vertical pulses unrelated to the explosions. The photographic evidence of the Rosenquist photos shows that at least the largest seismic pulse coincides with observed explosive activity. Also, a sequence similar to the three decreasing pulses from 22-103 secs occurred during a smaller eruption on August 8, 1980. The similarity of the waveforms in the August 8 and May 18 events argues that the source of the three pulses is not unrelated to the explosions. The series of pulses could be a natural consequence of the dynamics of rapid degassing of a viscous fluid. In this case the thrusts still correspond to ejected mass and the mass balance in Fig. 1b still holds. Another possibility is that the decreasing train from 22-103 secs (Fig. 2) represents reflection due to a single force. A simple seismic reflection from the Moho or some other geological feature would have occurred far faster than the observed 25-30 secs between peaks. An atmospheric reflection would have been slower. However, it is possible that the pulses are reverberating waves in the magma body. It has been proposed that the main magma body was at approximately 7-9 km below the cryptodome [*Scandone & Malone,* 1985]. If the waves travelled at the p-wave velocity through the unfragmented magmatic conduit connected the upper and lower chambers, the two-way travel time might be the requisite 25-30 secs. If the train of pulses are a series of reverberations, the total energy of the waves would be less than or equal to the total energy in the original wave from the real force. To first order, the real force applied at the time of the first peak would be equivalent to the sum of the three observed peaks. Hence, the total mass discharged would be the same as that intially estimated in Fig. 1b. This first order estimate can be refined by accounting for the fact that it is the sum of the energy of the three pulses that is conserved rather than the sum of the forces. Equivalently,

$$\int_{t_1}^{t_2} \delta^2 dt = \int_{t_1}^{t_4} (\delta_1^2 + \delta_2^2 + \delta_3^2) dt \tag{2}$$

where δ_1, δ_2 and δ_3 are the amplitude of the seismic strain waves corresponding to the pulses with forces F_1, F_2 and F_3 in Fig. 2a and δ is the amplitude of the Lamb pulse that would correspond to the real force in Fig. 2b. The times t_1, t_2, t_3 and t_4 are the beginnings and ends of each pulse as marked. Since the amplitude of the seismic waves is proportional to the force [*Kanamori et al.,* 1984], Eq. 2 can be rewritten

$$\int_{t_1}^{t_2} F^2 dt = \int_{t_1}^{t_4} (F_1^2 + F_2^2 + F_3^2) dt. \tag{3}$$

The forces are assumed to be equivalent to mass flux by Eq. 1 and therefore Eq. 3 can be written as an expression for the second moment of $\dot{M}$,

$$\int_{t_1}^{t_2} \dot{M}^2 dt = \left(\int_{t_1}^{t_4} (F_1^2 + F_2^2 + F_3^2) dt \right) / v^2. \tag{4}$$

If we assume that the real mass flux $\dot{M}$ was a triangular pulse that lasted from t_1 to t_2 then the integrated mass discharged can be derived in terms of the apparent forces F_1, F_2 and F_3,

$$\int_{t_1}^{t_2} \dot{M} dt = \frac{\sqrt{3(t_2 - t_1) \int_{t_1}^{t_4} (F_1^2 + F_2^2 + F_3^2)\, dt}}{2v}. \tag{5}$$

The mass history as recalculated with Eq. 5 to account for the reverberations is plotted in Fig. 1c. The preferred model has significantly more mass ejected earlier in the eruption, but the total mass ejected is only slightly less than in the preliminary calculation in Fig 1b. The correction for reverberations is minor.

Even though hypotheses (a) and (b) explain part of the force history, the preferred model that results in Fig. 1c still requires that most of the mass was ejected vertically. At this point it is appropriate to reexamine the major evidence for a high-speed horizontal. 1) The blast surge overtook the original debris avalanche. In order to be moving faster than the gravity-driven flow an initial impulse is commonly assumed to be necessary. 2) Photographs are interpreted to show a lateral, high speed jet.

The high speed of the blast surge could have resulted from high mobility rather than initial momentum [*Glicken,* 1996]. Since the pyroclastic material had more gases involved, the frictional resistance would be lower and the speed would be faster. In the absence of a quantitative understanding of long-runout gravity flows it is difficult to be more precise about these frictional effects.

The Rosenquist photographs provide the most continuous record of the eruption. Using a timing by S. Malone (written communication, 1998) the initial small vertical plume was followed by a large expansion at around 8:32:47, the time of the largest vertical pulse. This is consistent with the interpretation of the pulses as related to explosive activity rather than merely being perturbations of the landslide. The trajectories of the blast clouds reach angles as high as 70° with the horizontal, however the vent itself is obscured. As soon as the jet left the vent it would have begun to bend towards the horizontal so the observed orientations of 70° are not inconsistent with a blast angle of greater than 80°.

Implications

The above discussion indicates that most of the "lateral" blast was initially ejected vertically. The high lateral velocities that ultimately occurred in the devastated area were a consequence of the flow accelerating downslope under the influence of gravity. The entire blast deposit was primarily gravity-driven. This is not an entirely novel hypothesis [*Sparks, R.S.J., et al.,* 1997]. *Malin & Sheridan* [1982] even explain the extent of the blast deposits with a gravity model. However, it can now be substantiated with seismic evidence.

A vertical rather than horizontal initial impulse does not change many of the fundamental predictions of the most complete blast model [*Kieffer,* 1981] such as the sonic mass flux at the vent or the supersonic formation of furrows, but it does fundamentally affect predictions of jet structure. Specifically, the prediction of the location of the Mach disk because unsustainable. *Kieffer [1981]* explains a transition from directed flow to channelized flow about 11 km north of the vent as a Mach disk separating supersonic and subsonic flow. An upward directed blast is still predicted to be supersonic because of the extremely low sound velocity of the dusty gas, but the importance of gravity for accelerating the flow downwards invalidates specific scalings of jet structure. Since the flow is driven forward primarily by gravity rather than the initial impulse, the free jet structure is not appropriate. *Kieffer* [1984] notes that "the most highly supersonic zone and the Mach disk happen to coincide with a region of very steep topography." This may not be a coincidence. I speculate that the steep drop in topography acts as a diffuser and hence decelerates the flow to subsonic. I offer this as an alternative explanation for the observed change in flow character.

In conclusion, the lateral blast of Mt. St. Helens May 18, 1980 can best be described as a supersonic gravity-driven flow. Purely momentum-driven models neglect an integral part of the physics of lateral eruptions. Researchers who are attempting to assess volcanic hazards should be aware of the importance of gravity in controlling lateral blasts.

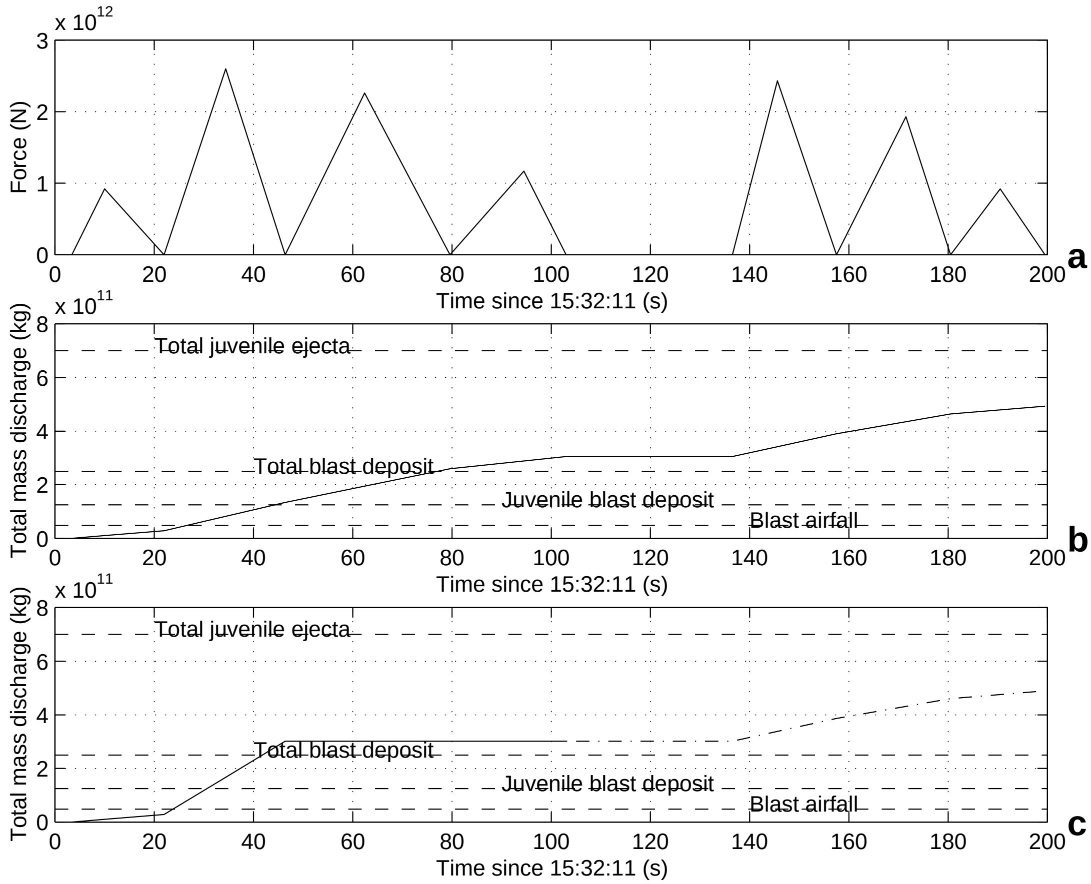

Figure 1. (a) Force time history from seismic data of *Kanamori et al.* [1984]. (b) Preliminary estimate of mass ejection using data in (a) and Eq. 1 with v=300 m/s. (c) Preferred vertical mass ejection history with v=300 m/s. The third and forth pulses are interpreted as reverberations. The mass from the pulses after 130 sec (the dot-dash line) is not new material at the vent and hence is not relevant for discussions of the blast dynamics. (See text.)

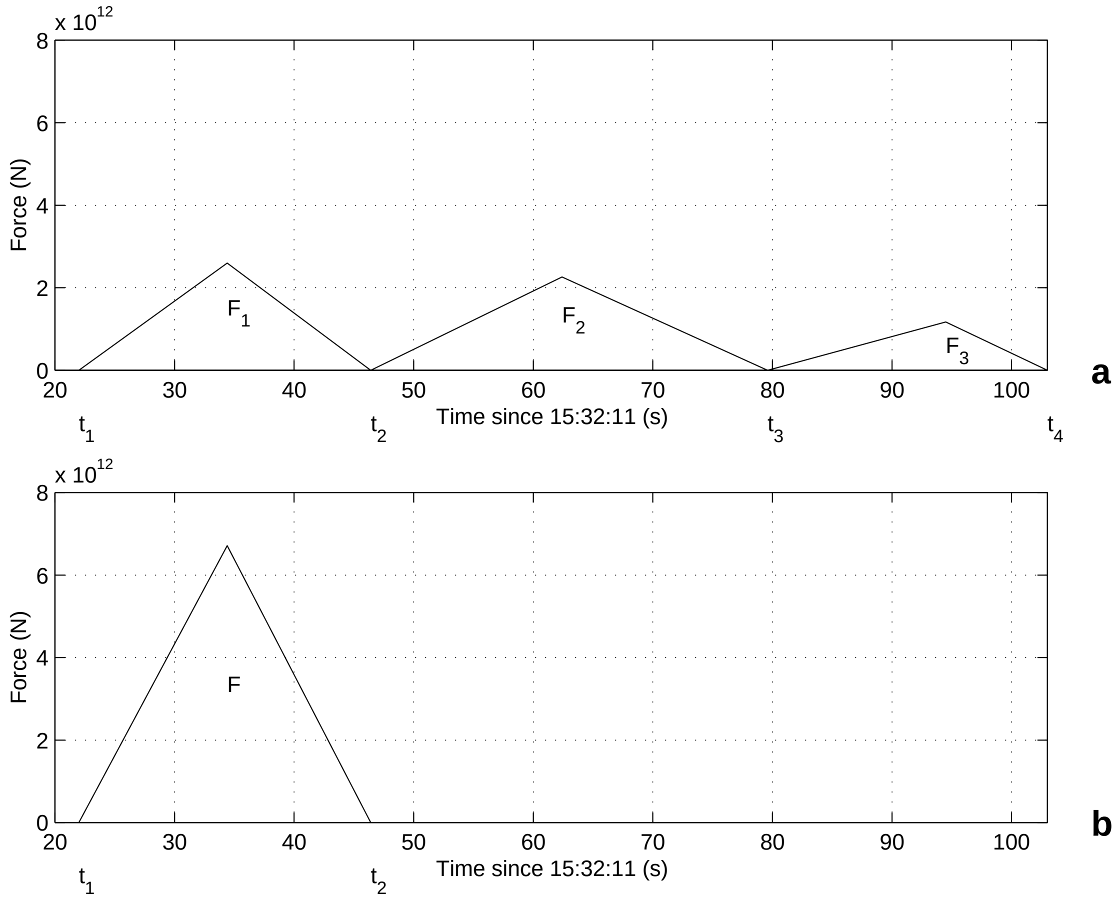

Figure 2. (a) An expansion of the train of three pulses from Fig. 1. These pulses most likely represent reverberations in the magma body and are labelled F_1, F_2, and F_3. (b) A single pulse F that corresponds to the energy released in the series F_1, F_2 and F_3.

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